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METHOD OF CALCULATION OF TURBULENCE EFFECTS FOR COMPUTER SIMULA--ETC(U)

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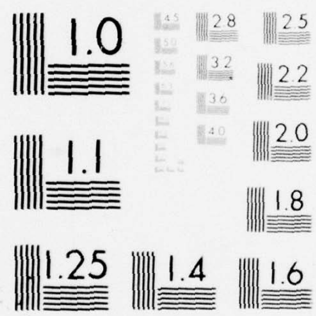

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TECHNICAL REPORT RE-CR-77-4

METHOD OF CALCULATION OF TURBULENCE EFFECTS FOR COMPUTER SIMULATION OF LASER SENSOR POINTING JITTER PERFORMANCE

Optical Science Consultants
P. O. Box 446
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June 1976

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U.S. ARMY MISSILE COMMAN

Redstone Arsenal, Alabama

Prepared for:

Advanced Sensors Directorate
US Army Missile Research, Development and Engineering Laboratory
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This work calculates

The work started in Optical Science Consultants Report No. TR-203 is extended here to allow calculation of (1) the expected laser spot size, (2) a method of developing a propagation conditions parameter related to what an observer might be able to sense, and (3) the power spectrum for angle-of-arrival jitter due to turbulence in the propagation path between the laser spot and the laser sensor optics.

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CONTENTS

I. INTRODUCTION

This report has been prepared as an extension of the work reported earlier,* to apply the same techniques to a second set of turbulence-related problems in laser semi-active terminal guidance. The problems of interest here concern the following:

1) The expected size of the laser spot at the target.
2) Estimation of propagation conditions from the laser designator position.
3) Calculation of the power spectrum of the fluctuations of the apparent position of the laser spot, as seen by the laser-spot tracker.

These matters shall be discussed in the following sections. In general, a notation that is compatible with that of the previous work will be used and an awareness on the part of the reader with the notation presented there will be assumed.

II. LASER DESIGNATOR SPOT SIZE

Laser designator spot size is determined by three factors. These are related to the following:

1) The diffraction-limited beam spread.
2) The turbulence-induced beam spread.
3) The deliberately induced transmitter beam spread.

The first two of these are most conveniently treated in combination, making use of the turbulence-limited, short-exposure resolution theory as developed** and applied.† The effective beam spread due to these two sources is shown to be given by the expression

*Fried, D.L., Computer Simulation of Turbulence-Induced Pointing Jitter for a Laser Designator, Optical Science Consultants Report No. TR-203, March 1976.

**Fried, D.L.,"Optical Resolution Through a Randomly Inhomogeneous Medium for Very Long and Very Short Exposures," J. Opt. Soc. Am., Volume 56, 1372, 1966, p. 11, Equation (18).

†Fried, D. L., Theoretical Study of Non-Standard Imaging Concepts. Final Technical Report on Contract No. F30602-74-C-0115, Rome Air Development Center Report No. RADC-TR-76-51.

$$\delta\theta_{1,2} = \theta_{ref}\,\mathcal{R}(D/r_o) \quad , \tag{1}$$

where

$$\theta_{ref} = 1.128\,\lambda/r_o \quad , \tag{2}$$

and

$$\mathcal{R}(D/r_o) = \left\{ \frac{16}{\pi}\left(\frac{D}{r_o}\right)^2 \int_o^1 u\,du\,[\cos^{-1}(u) - u(1-u^2)^{1/2}] \right.$$

$$\left. \times \exp[-3.44\,(D/r_o)^{5/3}\,u^{5/3}\,(1-u^{1/3})] \right\}^{-1/2} \quad . \tag{3}$$

The quantity r_o is defined by the expression

$$r_o = \left\{ 16.70\,\lambda^{-2} \int_{Path} ds\,C_N^2\,(s/R)^{5/3} \right\}^{-3/5} \quad , \tag{4}$$

where the integration path is from $s = 0$ at the laser designator to $s = R$ at the designated target range. C_N^2 is the refractive-index structure constant, λ is the laser wavelength, and D is the diameter of the laser designator aperture.* $\delta\theta_{1,2}$ may be taken to represent a full width at half maximum due to diffraction and turbulence beam spreading.

To combine this spread with that due to the deliberate defocus of the designator unit, where this spread is to a full width at half maximum of $\delta\theta_3$, a quadrature combination is utilized. Thus the following equation can be written for the laser spot angular spread due to all three causes:

$$\delta\theta_3 = [(\delta\theta_{1,2})^2 + (\delta\theta_3)^2]^{1/2} \quad . \tag{5}$$

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*Op. Cit., Computer Simulation of Turbulence-Induced Pointing Jitter for a Laser Designator.

At a range R, this corresponds to a spot diameter

$$\delta x_3 = R\,\delta\theta_3 \quad . \tag{6}$$

This is the size of the laser spot as projected on the target.

III. ESTIMATION OF PROPAGATION CONDITIONS

To form an estimate of the propagation conditions, it is suggested that the operator of the laser target designator view the target with high power optics (binocular-type optics) and try to find an edge or line on the target from which he can determine the turbulence-limited angular resolution. It is hypothesized that a trained operator will be able to judge by comparison the sharpness of such details with a set of reticle line-width markings what the turbulence-limited resolution is, and thus what the value of r_o is. In practice, he would simply be concerned with angular resolution, but it is more convenient to assume that he is evaluating an r_o related quantity. This quantity is denoted by $\mathcal{E}$ and defined as

$$\mathcal{E} = \int_{\text{Path}} ds\, C_N^{\,2} (R - s)/R \quad , \tag{7}$$

where s = 0 is at the observer/laser designator end of the propagation path and s = R is at the target end.

The smaller $\mathcal{E}$ is, the better the propagation conditions are. It is suggested that the quantity $\mathcal{E}$ be evaluated for all simulations and provided as a printout associated with the simulation. It is expected that to the extent that turbulence conditions influence laser target designation performance, the variations in $\mathcal{E}$ will be correlated to the variations in performance.

It should be recognized that this hypothesized relationship is only a plausible conjecture and presumes a certain well-behavedness of the turbulence conditions. For example, the range weighting in evaluating $\mathcal{E}$ is the reverse of that for the laser beam spread so that the relationship would be expected to hold only if the values of $C_N^{\,2}$ are reasonably symmetrically distributed along the propagation path. The use of $\mathcal{E}$ as a measure of the propagation conditions ignores real and pseudo wind velocity. This is based on the assumption that normal winds will be sufficiently fast that the operator will not be able to track out turbulence-induced pointing errors.

Assuming that the preceding conjecture regarding the relationship of the value of $\mathcal{E}$ to the turbulence effects on designator performance is validated by the computer simulations, it would then be necessary to demonstrate that an observer can, with as little equipment as a reticle in a pair of binoculars, form a reasonably accurate estimate of $\mathcal{E}$. This sort of thing has been done by Lincoln Laboratory viewing a specially prepared target board.* Field tests will have to be performed to see if acceptable results can be obtained using unprepared targets.

IV. ANGLE-OF-ARRIVAL FLUCTUATION POWER SPECTRUM

In addition to the turbulence-induced wander of the laser spot on the target, there is a second source of apparent target position jitter due to the apparent variations of the laser spot position associated with the viewing process. Even if the laser spot were perfectly stationary, its apparent position would fluctuate due to the turbulence in the path from the laser spot to the tracker optics. Associated with this process, there is a viewing process fluctuation power spectrum, $F_V(f)$, which should be added to the laser spot position power spectrum, $F_\alpha(f)$, calculated to yield the total power spectrum, $F_T(f)$, associated with the turbulence-induced jitter between the laser tracker reported target position and the actual target position.**

$$F_T(f) = F_\alpha(f) + F_V(f) \qquad . \tag{8}$$

It is $F_T(f)$ which determines turbulence contribution to the error in a laser target designator/laser semi-active seeker missile system.

For clarity of notation, D_V shall be used to denote the laser seeker optics diameter, and R_V to denote the range from the seeker to the target. Following the same analysis the nominal spectrum for $F_V(f)$ can be written as follows:**

***The Lincoln Laboratory experiment used a v-shaped pattern of pairs of lights; the observer noted how close to the vertex of the v he could resolve the pair of lights. He used this to infer r_0 and could have inferred the value of $\mathcal{E}$.**

**** Op. Cit. Computer Simulation of Turbulence-Induced Jitter for a Laser Designator.**

$$\tilde{F}_V(f) = \sum_{i=1}^{N_V} F_{V,1}(f) \quad , \tag{9}$$

where

$$F_{V,1}(f) = 1.32 \times 10^{-2} (\lambda/D_V)^2 (D_V/r_{0,V,i})^{5/3} F_{0,V,i}^{-1/3} f^{-2/3} G_V(f/f_{0,V,i})$$

The function $G_V(f/f_{0,i})$ is defined by the expression

$$G_V(f/f_{0,i}) = \begin{cases} 1 & \text{if } 0 \le f \le 0.332\, f_{0,V,i} \\ 1.12 - 0.361\,(f/f_{0,V,i}) & \text{if } 0.332\, f_{0,V,i} < f \le 3.10\, f_{0,V,i} \\ 0 & \text{if } 3.10\, f_{0,V,i} < f \end{cases} \tag{11}$$

Here the quantities $r_{0,V,i}$ and $F_{0,V,i}$ are determined by the local turbulence and effective wind characteristics in the i^{th} segment of the propagation path from the laser spot to the seeker optics. With $C^2_{N,V,i}$ denoting the refractive-index structure constant in the i^{th} segment, $V_{eff,V,i}$ denoting the effective wind velocity in the i^{th} segment, $z_{V,i}$ denoting the position on the z-axis of the midpoint of the i^{th} segment, and $\Delta z_{V,i}$ denoting the width of the i^{th} segment the following equation can be written:

$$r_{0,V,i} = [16.7\, \Delta z_{V,i}\, C^2_{N,V,i}\, (z_{V,i}/R_V)^{5/3}/\lambda^2]^{-3/5} \tag{12}$$

and

$$f_{0,V,i} = \frac{V_{eff,V,i}}{\pi D_V (z_{V,i}/R_V)} \quad . \tag{13}$$

It is to be recalled that $z_{V,i}$ is smallest near the laser spot and largest near the seeker optics.

The calculation of $\widetilde{F}_V(f)$ is straightforward and follows directly from the corresponding sample calculation presented.* In the case under consideration here, however, there is one more effect to be considered which makes it necessary to distinguish between $\widetilde{F}_V$ and F_V. This additional effect has to do with angle-of-arrival isoplanatism. Because of the size of the laser designator spot, δx_3, the turbulence-induced angle-of-arrival has different values for light arriving from different portions of the laser spot. This is due to a lack of angle-of-arrival isoplanatism.

To accommodate the lack of angle-of-arrival isoplanatism, it is suggested that the spot be considered to be subdivided into a set of N independent source regions for each of which $\widetilde{F}_V(f)$ applies, but for each of which the angle-of-arrival fluctuations are independent. Then, to a first approximation, the following equation can be written:

$$F_V(f) = F_V(f)/N \quad . \tag{14}$$

It can be seen that this formulation is only approximate. It is expected that the lower frequency angle-of-arrival fluctuations be correlated over a larger portion of the laser spot, while the higher temporal frequency fluctuations would be correlated over a smaller portion of the laser spot. To take this into account properly would involve a very complex calculation to develop a value for N as a function of temporal frequency f.

This complexity is avoided by arguing that it will be sufficient if the single value of N is chosen so that the resultant power spectrum $F_V(f)$ will correspond to the true variance of the effective angle-of-arrival, i.e., angle-of-arrival averaged over the total laser spot. In this way, there is assurance that although there may be some distortion of the power spectrum of the effective angle-of-arrival for viewing the laser spot, the power spectrum will yield the correct total variance of the angle-of-arrival.

To determine N, an angle-of-arrival isoplanatism angle, ϑ_0 must be defined. This angle is defined as the angular separation of two point sources

*Ibid.

such that the correlation of angle-of-arrival fluctuations for the two sources is just one-half of the variance of the angle-of-arrival for either source. Then it may be considered that there are

$$N = 1 + \left(\frac{\delta x_3}{R_V} \Big/ \vartheta_0 \right)^2 , \tag{15}$$

independent regions on the laser spot. The problem at this point clearly reduces to that of determining ϑ_0.

The subject of angle-of-arrival isoplanatism has previously been studied.* It has been shown that the mean square difference in angle-of-arrival from two point sources separated by an angle ϑ can be written as**:

$$D_{1,\alpha}(\vartheta) = D^{-1/3} \int_{\text{Path}} ds\, C_N^2\, F_\alpha(\vartheta s/D) \tag{16}$$

where

$$F_\alpha(\xi) = 2.91 \int_0^{2\pi} d\phi \int_0^1 u\, du\, K_\alpha(\phi, u)\, Q(\phi, u; \xi) \tag{17}$$

with

$$K_\alpha(\phi, u) = \frac{1}{2}(16/\pi)^2 [\cos^{-1}(u) - u(1-u^2)^{1/2} - 2u(1-u^2)^{3/2}] \tag{18}$$

and

$$Q(\phi, u; \xi) = \frac{1}{2}[u^2 + 2u\,\xi \cos\phi + \xi^2]^{5/8}$$

$$+ \frac{1}{2}[u^2 - 2u\,\xi \cos\phi + \xi^2]^{5/6} - u^{5/3} - \xi^{5/3} \quad . \tag{19}$$

*Op. Cit., Theoretical Study of Non-Standard Imaging Concepts, p. 107 et seq.
**Ibid., p. 135, Equation (2).

As presented, Equation (16) applies for an infinite plane wave source and $s = 0$ corresponds to the location of the sensor optics of diameter D. To take account of the point source nature of the matter, a factor of $[(R_V-s)/R_V]^{5/3}$ is introduced into the integrand* in Equation (16). Moreover, to maintain consistency with our other formulations, the variable of integration is reversed so that $s = 0$ corresponds to the laser spot position and $s = R_V$ corresponds to the sensor optics position. Moreover, taking note of the fact that the sensor optics diameter is denoted by D_V for this problem, the following equation can be written in place of Equation (16):

$$\mathcal{D}_{1,\alpha}(\vartheta) = D_V^{-1/3} \int_{\text{Path}} ds\, C_N^2 \, (s/R_V)^{5/3} \, F_\alpha [\vartheta (R_V - s)/D_V] \quad . \tag{20}$$

The evaluation of $F_\alpha(\xi)$ is a straightforward, if tedious, numerical calculation based on Equations (17), (18), and (19). These calculations have been carried out and the numerical results listed in the table were obtained. In terms of a computer calculation, it is suggested that interpolation on the data in the table, rather than performance of the two-dimensional integration of Equation (17), is the preferred approach. In either case, $F(\xi)$ is considered to be a well-defined function and attention may be redirected to the calculation of the angle-of-arrival isoplanatism angle, ϑ_0.

The mean square difference in angle-of-arrival as a function of angular separation is equal to twice the angle-of-arrival variance minus twice the angle-of-arrival covariance, i.e.,

$$\mathcal{D}_{1,\alpha}(\vartheta) = 2 [\sigma_\alpha^2 - C_{1,\alpha}(\vartheta)] \quad , \tag{21}$$

where σ_α^2 is the angle-of-arrival variance, and $C_{1,\alpha}(\vartheta)$ is the covariance as a function of angular separation, ϑ. When ϑ is very large, the covariance vanishes and

$$\lim_{\vartheta \to \infty} \mathcal{D}_{1,\alpha}(\vartheta) = 2\, \sigma_\alpha^2 \quad . \tag{22}$$

*Ibid., p. 120, Equation (19).

Thus, the angle-of-arrival isoplanatism angle, ϑ_0, can be defined for which the covariance is equal to one-half the variance, i.e.,

$$C_{1,\alpha}(\vartheta_0) = \frac{1}{2}\sigma_\alpha^{\ 2} \quad , \tag{23}$$

by the expression

$$\mathcal{D}_{1,\alpha}(\vartheta_0) = \frac{1}{2}\mathcal{D}_{1,\alpha}(\infty) \quad . \tag{24}$$

Making use of the data in the table, the following equation can be written from Equation (20):

$$\mathcal{D}_{1,\alpha}(\infty) = 11.97\, D_V^{\ -1/3} \int_{\text{Path}} ds\, C_N^{\ 2}\, (s/R_V)^{5/3} \quad . \tag{25}$$

With the value of $\mathcal{D}_{1,\alpha}(\infty)$ thus specified, it is then a straightforward matter to iterate on the evaluation of $\mathcal{D}_{1,\alpha}(\vartheta)$ as defined by Equation (20) to find a value of ϑ for which $\mathcal{D}_{1,\alpha}(\vartheta)$ is one-half the value of $\mathcal{D}_{1,\alpha}(\infty)$ as calculated from Equation (25). This value of ϑ corresponds to ϑ_0.

With ϑ_0 evaluated, Equation (15) may be used to calculate N. The evaluation of $F_V(f)$ from $\tilde{F}_V(f)$ is then a trivial matter. The calculation of $\tilde{F}_V(f)$ has been set up in Equations (9) to (13). The final evaluation of $F_T(t)$, the total observed laser spot position fluctuation, including both transmitter and receiver jitter, incorporating the calculations* is now a straightforward matter.

*Op. Cit., Computer Simulation of Turbulence-Induced Pointing Jitter for a Laser Target Designator.

TABLE. CALCULATED VALUES OF $F_\alpha(\xi)$

The values of ξ in the table are logarithmically uniformly spaced, four to a decade, (viz. $1.778 \equiv 10^{1/4}$, $3.162 = 10^{2/4}$, $5.623 = 10^{3/4}$).

ξ	$F_\alpha(\xi)$
1.000×10^{-3}	1.069×10^{-6}
1.778	3.376
3.162	1.067×10^{-4}
5.623	3.376
1.000×10^{-2}	1.067×10^{-3}
1.778	3.377
3.162	1.066×10^{-2}
5.623	3.356
1.000×10^{-1}	1.049×10^{-1}
1.778	3.204
3.162	9.205
5.623	2.257×10^{0}
1.000×10^{0}	4.019
1.778	5.462
3.162	6.635
5.623	7.598
1.000×10^{1}	8.392
1.778	9.047
3.162	9.588
5.623	1.003×10^{1}
1.000×10^{2}	1.040
1.778	1.071
3.162	1.096
5.623	1.116
1.000×10^{3}	1.134
1.778	1.148
3.162	1.159
5.623	1.169
1.000×10^{4}	1.177
1.778	1.183
3.162	1.189
5.162	1.193
1.000×10^{5}	1.197

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